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Pile foundations: Traditional predictions and control reassessed by statistics

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ABSTRACT: Employing two sets of ample and good data from projects of driven precast concrete piles, with good numbers of load tests, the authors resort to unpretentious statistical regressions, with their dispersions, to explain, correct, and redirect, the principal more traditional and published procedures in use for design and quality control of driven pile foundation projects.

1 INTRODUTION

In recent times Geotechnical presentations and publications are being eagerly directed towards RECENT DEVELOPMENTS always giving the impression of top priority for episodic creativity, second order discoveries by serendipity, EUREKA. Yet I have persistently emphasized that the BASIC PROBLEMS OF PROFESSIONAL PRACTICE continue essentially the same, although with progressively increasing difficulties, both because of decreasing options in the choice of sites of preferred geologic-geotechnical conditions, and because of increasingly stringent requirements of the engineered end-product. Thus we have to formulate and face the problems and solutions as EVER INSUFFICIENTLY RIGHT EXCEPT BY TRANSIENT DECISION, always associated with COEFFICIENTS OF ADJUSTMENT associated with experience and the precisions of OBSERVATION FOR SUCH EXPERIENCE, and therefore always requiring a NEW AND UPDATED VISION, with recognition of dispersions, and, in automatic sequence, with the persistent search for tightening the dispersion band.

The field of driven precast piles is one of widest use in foundations: it has always been, and continues to be, treated by piling contractors with a high degree of confidence, notwithstanding the investigations and academic publications having systematically renegated it (Cummings, 1940; Sorensen, 1957; Flaate, 1964; Olson, 1967; Poulos, 1980; Liang, 1997). The frequency of such studies has only increased since obviously across decades nobody dares to formulate new dynamic formulae, the old ones continue to dominate the routine orientation of the foundation jobs, and the critical a posteriori studies multiply, be it in order to compare the driven piles with the bored ones (with a market understandably in expansion), be it in order to orient revisions of FOUNDATION CODES.

Since Smith (1955, 1960) the Wave Equation formulations have been recognized and improved for the desired orientation of driven piling. And already over a dozen years the Dynamic Load Tests DLTs (Goble, 1980; Aoki, 1991; de Mello, 1993) have been developed and applied on some piles of each piling project, with a recognized and publicized success regarding minimizing the requirements and burdens (logistic and economic) of the Static Load Tests, SLTs.

In principle, therefore, in any job of importance the final goal is only satisfied with execution of a few (1 to 2; $\leq$ 1%) SLTs (confirmatory, expensive, a-posteriori, most often risking not to pertain to the representative statistical universe); a small universe (6 to 12; 2 to 3% ?) of the piles merits being partially confirmed by DLTs; and the entire piling depends intrinsically on the GUARANTEE OF HOMOGENEITY OF THE RESULT based on the quality control provided by construction procedures reasonably related cause-effect.

This is the reason why the use of Dynamic Formulae DFs persists, according to the preferences of each piling contractor for one or another of the classic DFs.

We estimate that within professional practice the trust that the "set" and/or "rebound" furnish a good index of the QUALITY CONTROL OF HOMOGENEITY is immovable. And, from the observation of the near inexistence of undesirable behaviours of driven precast piles, despite the very limited data-base of SLTs and DLTs, results the inexorable intuitive conclusion that this apparent SUCCESSFUL HOMOGENEITY implies that we are working much more in accordance with very conservative PRESCRIPTIONS than via CORRELATIONS (WITH THEIR DISPERSIONS AND RESPECTIVE RISKS). We recall herein the experience (de Mello, 1987) in diverse fields of decision-taking, that the human being is about 70% more prone to decide in the direction of avoiding loss than in that of attempting gain. Thus, we can only conclude that in the majority of decisions of extrapolating from the statistical experimental universe already established (in the neurological computer) the decisions were being successively taken TO THE SIDE OF SAFETY (N.B. If in some cases they did not result effectively safer, it must have been by mistaken notions on the cause-effect influence of the specific parameter).

For greater simplicity of this presentation we shall limit it to driven precast reinforced concrete piles.

2 POSSIBLE INTERESTS BROACHABLE, AND SPECIFIC PURPOSE CHOSEN FOR THIS PRESENTATION.

In summary let us follow the routine sequence (unsubstitutable in 99% of the routine professional cases) of investigation, interpretation, design, PRELIMINARY technical specifications, bidding, contracting, and start of the job... and let us consider the needs, step by step.

We emphasize that we are setting aside one aspect that in present-day construction practice has come to be handled in a manner very prejudicially confused. It is the SPECIALIZED PILING CONTRACTOR that really applies with priority his experience for the execution of the piling, and so it has to be, both by the basic legal and professional concept of responsibilities, and because of the most profitable practice within the subdivisions of aptitudes. Thus, the EFFECTIVE TECHNICAL SPECIFICATIONS (obliged to demonstrate having met the formal requisites, with full cognizance of the preliminary Technical Specifications of the Designer, but without assuming the obligation to adopt them as impositions in the details) will really be those that will have been formalized by the Contractor in his Bid, alongside with the ulterior adjustments that may have to be incorporated UNDER HIS RESPONSIBILITY AND AT HIS EXPENSE.

In our analyses for this paper we discuss the facts both known and unknown, without attempting to separate among the diverse and successive components leading to the job's conclusion.

2.1 *Prediction of pile length, and of the corresponding preliminary technical specifications for driving.*

We report herein to boring profiles with SPT values (but in principle the same applies to any vertical index-profiling such as CPT etc.. that may eventually be taken as better). Moreover, we limit our discussion to two "typical" cases of Sao Paulo in which the EXECUTION EFFECTS of the pile itself are anticipated and accepted as being of secondary importance, also meanwhile foregoing the distinction between sands and clays.

This step comprises two big independent tasks in order to compose the single final goal...THE PILE RENDERED ADEQUATE. One the one hand it depends on the homogeneity/dispersions of the SPT boring profiles with which to associate the soil-pile interaction. There is always the need to estimate (for the sake of justifying alternate projects under choice) on the basis of the vertical profile (of SPT etc.) what will be the minimum penetration length *Lok.* which may guarantee that the resistance provided by the soil-pile interaction is at least equal to (or a little bigger than) the resistance permitted for the concrete section as a "structural element". Thus, we seek to associate an $Lok. = f_1$ (SPT). On the other hand it depends on the homogeneity/dispersions of the driven lengths L, associated with the working loads $Qwork = f_2(Lok.) = f_3$ (SPT).

Intuitively one seeks the hope that the above functions may not be basically ridiculous, through such supporting insinuations as

(a) a possible analogy between driven SPT and driven pile L;

(b) the same driving energies (and corresponding parameters) should compensate with bigger L's the positions of soils of lower SPT, and vice versa.

2.2 *Driving quality control of the entire piling job.*

Once the pilot-driving has started, preliminarily oriented as per 2.1, one seeks to improve the orientation on READJUSTMENTS SPECIFIC TO THE JOB (N.B. We do not know of any cases in which further mini-readjustments may have been applied to different groups of piles per block, generally varying between 1 and 6, although in principle it would be quite justifiable).

At this stage the aims become diametrically opposite (a) of the Contractor, in the direction of minimizing the adjustments (especially inasfar as they affect costs and profits); (b) of the Inspection, in the direction of maximizing the Ls in order to guarantee with regard to long-term ulterior behaviours.

However, in principle each pile continues to be driven under two basic aims: (i) guarantee *Lok* for *Qwork* $\geq$ *Qwork* SPECIFIED; (ii) guarantee homogeneity. The entire piling is driven under such rudimentary driving criteria, oriented by the conventional indices of the "Dynamic Formulae D.F.", Energy E, Set s, and Rebound r, etc.

2.3 *More specific and modern orientation based on Dynamic Load Tests DLTs, determined via the Wave Equation and recordings of vibrations interpreted by computer programs.*

The DLTs can be performed rapidly and economically, on 6 to 8 piles per day, alongside of the very work of driving of the piling, thus furnishing load-settlement curves which, for small settlements, have been proven to simulate quite well the Static Load Tests, SLTs. Thereupon, under a sequential reasoning it is profitable to establish the links between the rudimentary technical monitoring of the driving (DFs) and the more sophisticated monitoring of a certain number of DLTs.

In the face of this aim it should be very interesting that a series of successive DLTs should be performed on the selfsame pile while its L is being progressively increased (jointly with the alterations of the rudimentary indices of the DFs of the driving). For statistical purposes one should need several analogous series. Such information is presently essentially inexistent, as a result of which this constitutes the biggest missing link in the field of precast driven piling. Perhaps the explanation might be easy, under two dominant syndromes of scientific insufficiency: one, that the DFs were worthless, irrecoverable, meriting being forgotten in totum : the other, that in the face of the insistent critical teachings regarding the major differences between dynamic and static behaviors, and the enormous practical advantages of the DLTs, the essential and priority need was to establish the link DLT$\approx$SLT.

We emphasize that the acceptable applicability of the above procedure requires that one should test with different Ls already within the maximum range of sets experienced in practice, for example $1 < s <$ 20cm , in order that we avoid mixing conditions of clear penetrability (in which the bigger deformations thwart the resemblance of static $\approx$ dynamic, DLT $\approx$ SLT) and those of set conditions. As a result very often the variation of L will be small, increasing the dispersions of the statistical regressions.

As we shall explain below, what is most lacking, in order to attenuate the tendencies to executing piling jobs more conservatively and expensive than necessary, would be the link D.F. $\rightarrow$ DLT; all the more so because the link DLT $\rightarrow$ SLT sets aside, for the present, the bigger diameter piles.

2.4 *Checking on the adequacy of the piling in the face of Codes and Standards, by way of Static Load Tests, SLTs.*

Depending on the subjective evaluation of the importance of the piling and/or of its problems, at some phase of the project one performs a few (1 to 3?) Static Load Tests SLTs; in the vast majority of cases they are oriented limited to the aim of DEMONSTRATING THAT THE REQUIREMENTS OF THE STANDARD HAVE BEEN MET. [N.B. In passing let us recognize that many are the projects in which no SLT is performed, regardless of the recommendation of the Code]. Thereupon, since there is no incentive towards really testing in totum, taking the load up to the real failure, in the largest percentage of available data one only concludes that the Qfail will be higher than the load reached up to the limiting load (of the kentledge or anchors dimensioned for economy, since the design of the piling project, already defined, would not be benefited by higher results of the load test). Also, as a general rule the piles for SLT testing tend to be those that had given worst indices of set/ rebound (among the partially completed piling); and also, because of problems of logistics, it is rare that the SLTs coincide with previously tested DLTs (besides the time difference as affecting set recovery).

In summary, the DLTs and SLTs are not progressively decreasing samples of the same random statistical universe; the results of the SLTs (whatever may be the interpretations of the load-settlement curves) tend to be lower-bound values of the universe, and VALUES THAT IN THE VERY SELFSAME PILES ONLY WOULD TEND TO BE HIGHER THAN THOSE OBTAINED IN THE RESPECTIVE SLT.

2.5 *Final proof of the adequacy of the piling in the face of the performance of the superstructure.*

Regrettably we have to recognize that in almost the total universe of foundations of buildings, residential or commercial, the piling seeks to meet formal requisites which the civil-structural construction engineering has not bothered to have considered as meriting cause-effect monitoring, loads, settlements, Δ(*loads*), Δ(*differential settlements*), damages. The cases of tanks etc...have very well-defined loads, and practically no tendency at all towards increases of loadings. The cases of high buildings, with their wall panels of brick tightly wedged, have NOMINAL LOADS (almost never have they been measured at the bases of the columns), and load-redistributions due to rigidity (as soon as differential settlements begin) also hitherto completely unknown. [N.B. One is astonished at the lack of curiosity and spirit of technological quest in the face of a "park" of buildings like that of Santos, so analogous, and so sadly "rich" in differential settlements and corresponding damages]. The Codes and Standards avoid a realistic approaching of the problem.

From popular experience one recognizes, however, that very few cases of buildings on precast driven pilings have evidenced undesirable performances, of fissures and cracks in the finishes (and eventually) in the structural frame. Such an indication has to be appreciated under a sequence of considerations: (a) such pilings tending to be very conservative; (b) these piles generally giving insignificant settlements up to the working loads, together with accelerations of the settlement/load gradients in the pre-failure phase; (c) fissuring of the finishes can only be generated after the finish is executed, and therefore practically being due to delayed settlements and/or due to increments of live loads; (d) insinuation of conditions of start of plastification (pre-failure) emphasizing the concern for Qfailure; (e) the difficulties of executing any eventual reinforcement (underpinning), if called-for, in the case of driven piles and a completed and occupied building.

In the task of appreciating the "proof of the pudding" of the project completed to satisfaction, let us recognize our automatic bias of only considering the building as performing well, frequently better than necessary. Let us not assert that buildings with settlements, say, of 4cm would perform unfavourably, in comparison with those that settle only 1cm: we just do not know. We know, however, that we overlook the other side of the balance: of a foundation contract satisfactorily completed regarding logistics and prices and costs, without the burdens of eventual exaggerated requirements, unjustifiable. Somebody, Society, pays the prices of unjustifiable requirements. Further along we shall see that one tendency of increased cost is being that of the increase in the number of piles broken in driving.

2.6 *Special cases meriting consideration.*

In the face of the needed bases for orienting the piling, we must needs submit in passing certain specific considerations that also enter in certain cases, but that have merited little exposure in publications;

1) To judge on the "penetrability" (and means to guarantee it) for traversing hard strata;

2) To evaluate maximum driving stresses, be they of compressions/crushing, be they of tensile reflections, in order to avoid breakages;

3) To seek (in rarer cases) indices for evaluating the deformabilities up to the working load; etc.

The present paper excludes any of these less frequent considerations.

3 TWO REASONABLY WELL DOCUMENTED CASES PRESENTLY ANALYSED.

Fig.1 presents schematically two cases of precast concrete driven piles, which, for different reasons, merited construction monitorings more meticulous than routine. Case A basically faced the need to meet imposed Foundation Code requirements, under the geotechnical peculiarities of: a) representing a pile-driving with preboring, practically without lateral friction, b) with the point resistance obliged to guarantee itself in a dense saprolite horizon of granite-gneiss, which is recognized to give wide dispersions of SPT values, c) light-section piles with driving limited by risks of breakage. Case B involved a novel type of foundation project for a residential building of stringent requirements, and employing driven piles as LOAD REDUCERS FOR THE FINAL EFFECTIVE PHASE OF LOADING-SETTLEMENT, in a condition of: a) sedimentary strata presumed to be homogeneous in the range of practical experience; b) a specific interest in homogenization of mini-behaviors of ulterior load-settlement; c) relatively robust piles, cumulative friction-point soil reaction.

The technical specifications indicated the customary sets s (and, much less frequent, rebounds r) without specific references to Energies E, dynamic formulae DFs, etc.. Both cases ended up having a good number of DLTs which were normalized to reasonably analogous conditions for grouping into idealized statistical universes.

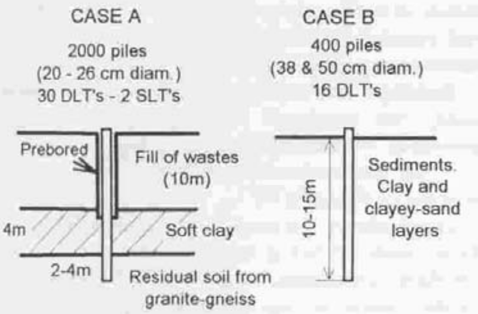

Fig. 1 - The two cases used for discussion

3.1 *Attempted simple regressions on single parameters.*

Fig. 2 reproduces the unpretentious single parameter regressions, the only ones that have hitherto entered (timidly) into geotechnique. One dispenses commenting the correlation coefficients R^2 so low that they exclude any hypothesis of one really dealing with CORRELATIONS; the pilings are being driven to OVERABUNDANTLY SATISFY PRESCRIPTIONS, forecasting indices, and corresponding loads, definitely higher than the minima sought (limited only by the risks of breakage). [N.B. Note, in passing, that there do not seem to exist, in the practice of profession, the driving indices associated to breakage risks, another factor of considerable importance for the economic optimization of the job]. The dispersions, however, appear shocking: on the side of the rejection criterion, of minimum requirements, these dispersions when "normalized" Gaussian, would still indicate a fractile (insignificant) of extreme cases beyond the boundaries.

In order to assess the matter with the maximum of data rendered analogous despite the (small) differences of piles used, we decided to transform the Qfail of the DLTs into stresses on the concrete (the external nominal section), i.e., the stress (applied to the pile head of each case) which presumably led to pile-soil deformations taken as corresponding to those of failures (Fig.3). We signal in these same Frequency Curves the positions of the allowable stresses (as per catalogues) on the respective pile-structures. Finally, adopting the normalized Gaussian frequencies, we determined the stresses corresponding to recurrences of less than 10% and 5% respectively, of probabilities of the nominal failure stresses resulting smaller.

It will probably be found shocking to conclude that in as much as 10% of the cases, for the usual

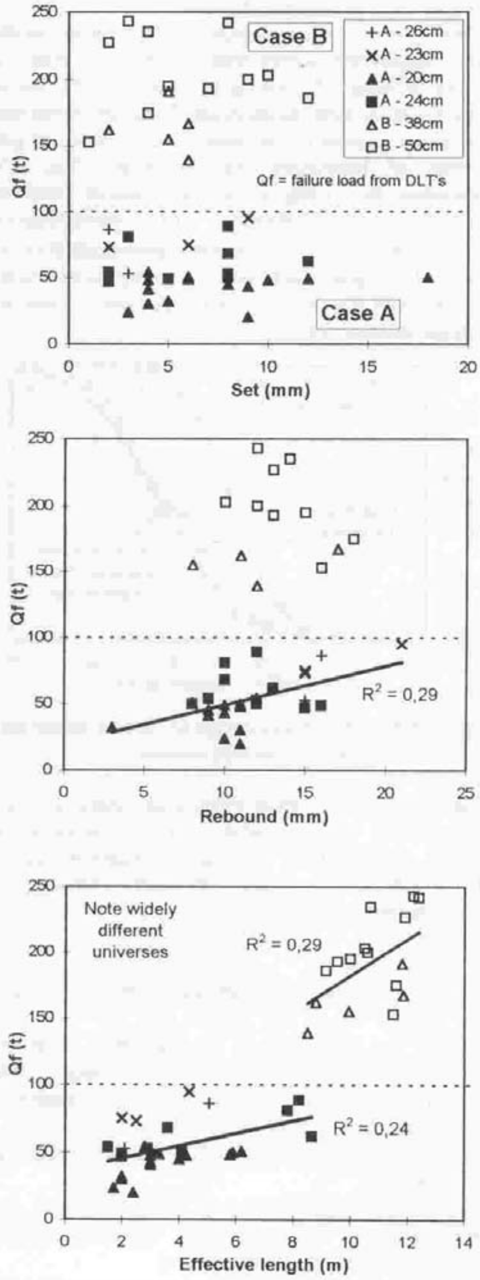

Fig. 2 - Single-parameter regressions attempted.

working loads employed with these piles and driving procedures, these piles would exhibit a Coefficient of Guarantee $CG \leq 1$, i.e. the piles would face some incipient pile-soil plastification, corresponding to an increased rate of settlement/load.*

What has to be emphasized is that these results show relative consistency with the aims that oriented the pile drivings. The driving of Case A tried to be as stringent as possible, to meet the Code, and furnished indications relative to the limits of drivability, as per number of breakages that occurred (Fig. 3). Meanwhile the driving in Case B sought to reach an eventual compatibilization of performances *Δsettlement / Δload* for the innovative-sophisticated design of composite behavior of footing (acting first) together with the pile centered under the column, to decrease ulterior deformability.

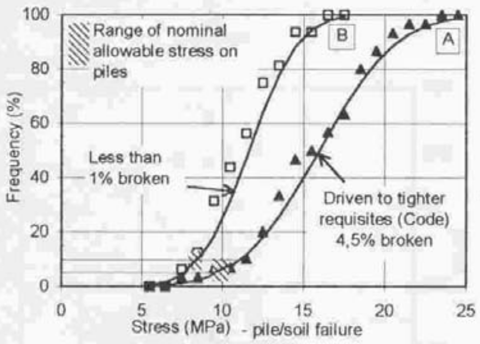

Fig.3 - Frequency distributions of "failure stress" on global concrete section.

What strikes out from these preliminary analyses is that there are rationales in the experience on driving; what has been missing is to admit it openly, and to submit the subject, markedly complex, to statistical regressions.

3.2 *Attempts at multiple regressions of the drivings.*

Without any presumption of any more than the meager knowledge of generalists in the matter of the support and quality-control providable by statistics, we cannot fail to note our surprise on:

a) the rarity of any MULTIPLE REGRESSION in geotechnique;

b) the practical inexistence of investigation and publication of CONFIDENCE BANDS around regressions, even the simplest ones;

c) the delay of some decades in comparison with, for example, the field of HEALTH;

d) the expensive concentration of effort in pseudo-scientific improvements of the few cases, of high concentrated investment, in comparison with the massive integration of millions of routine cases.

Seeking a first multiple regression along a logical trend, we employed the principal parameters associated with the static bearing capacity formula: i.e. , the geometries of friction and point, together with the EMBEDMENT *L* .

Fig. 4 shows the results, perceptibly favourable. As a matter of fact it would seem justifiable, as a corollary conclusion, that the REGRESSIONS resulted worse in case B, of the more robust piles driven differently. In gist, since the DLTs are part of the complete decision cycle set-out under items 2.1 to 2.5, we submit it as encouraging and promising to employ rationally-based multiple regressions.

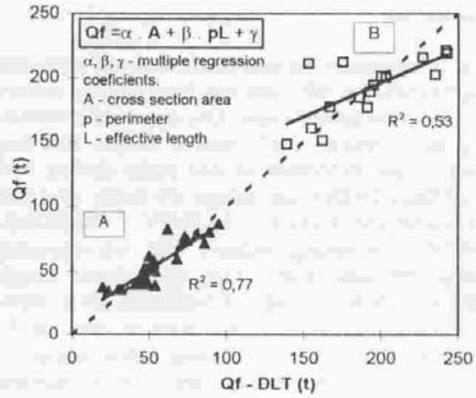

Fig. 4 - Example of benefit resulting from even a modest multiple regression.

3.3 *Would some rational and rationalizable trends prevail, with the rudimentary indices ?*

We sought thereafter to investigate the possible rationality of the rudimentary indices of Set and Rebound. Having accepted the progression (inexorable) of the resistances with the embedment (Fig. 2c) it happened, in Case A, during the exceptionally rushed job of completing the piling, that one had to resort to investigating and proving a RATIONAL RUDIMENTARY INDEX for orienting the increment sought. One imagined for this purpose to execute partial observations of sets and rebounds under successive increments of driving/penetration (embedment). We resorted to 18 piles with such drivings purposely interrupted, and thus achieved sets of 2 to 5 points per pile. Although we recognize that the records of sets and rebounds

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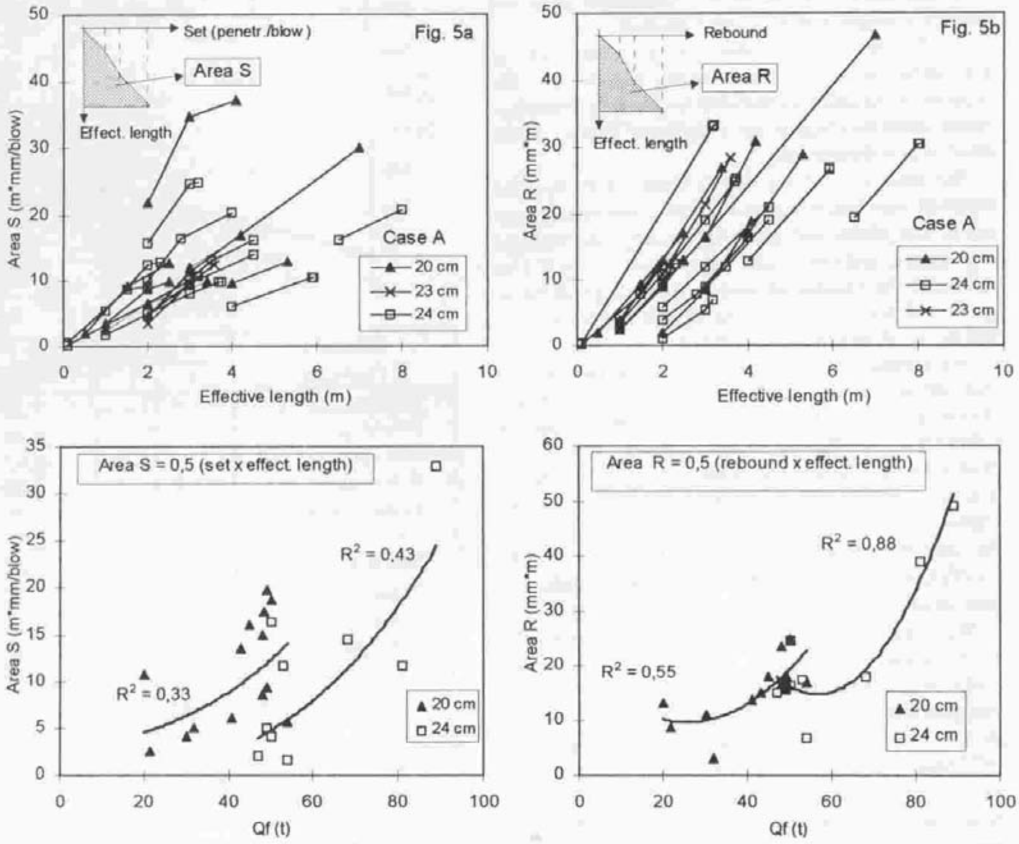
* *We refrain from repeating the many publications (de Mello, 1981) relative to the significant benefit of the Coefficient of Guarantee in comparison with the traditional Coefficient of Safety.*

were being obtained under unusual conditions, of values corresponding still to appreciable penetrabilities and not the typical "refusal" (s, r) values, their values were used, in idealized and simplified conditions, within the concept of integration (area) of effects. Thereby resulted the graphs of Figs 5a (set) and 5b (rebound) which we submit as quite eloquent in confirming the rationality of the concept and indices, even rudimentary. In order to seek further confirmation we plotted in Fig. 5c the graphs of the same two indices against the failure loads of the DLTs (of the other cases in which one managed to have the DLT performed). One sees that one manages to establish regressions meriting some interest, and, IMPORTANT, that the two piles taken as very similar resulted quite different. [N.B. There will be various means of seeking to improve the procedures adopted for computing the areas of integration of the indices of set, or rebound, or even others of promise: we refrain from delving into the subject because they should tend to indicate analogous trends, analogously rationalizable].

It must be noted here that one felt the worth that would ensue from the possible execution of some 2 - 3 DLTs on the same pile (and some other such piles of the same universe) in the course of rapid interruptions of the driving/penetration, recording the corresponding (L, s, r). Unfortunately the intense rush of the job did not permit it. It is doubtless a very strong recommendation for future cases.

In conclusion it only behoves us to: 1) advocate the intensifying of search and adjustments of multiple regressions, including as associated to DFs, for the pile-driving; 2) warn against exaggerations in the search for sophistications, determinisms, more refined numerical analyses etc.., of singular cases, in



5c - Demonstration of acceptable regressions for Qf from DLT's, from: a)set; b) rebound

Fig. 5 - Attempt to establish from rudimentary indices a rationalizable parameter for orienting length.

comparison with the fertility of a better feel for the significance of index-parameters on the basis of rationalizable regressions drawn from, and applied to, thousands of cases.

3.4 *Simplified regressions applied to the more current DFs, with their various parameters.*

Having accepted the thesis of the priority for multiple regressions, we have decided to expose below some relatively frustrating facts, that perhaps may have been responsible for the predominant impression of dissatisfaction with regard to the DFs (while abstaining from repeating the fully covered criticisms regarding the theories of impact, work, impulse, etc...from which they derive).

1) The most favourable regressions vary from case to case;

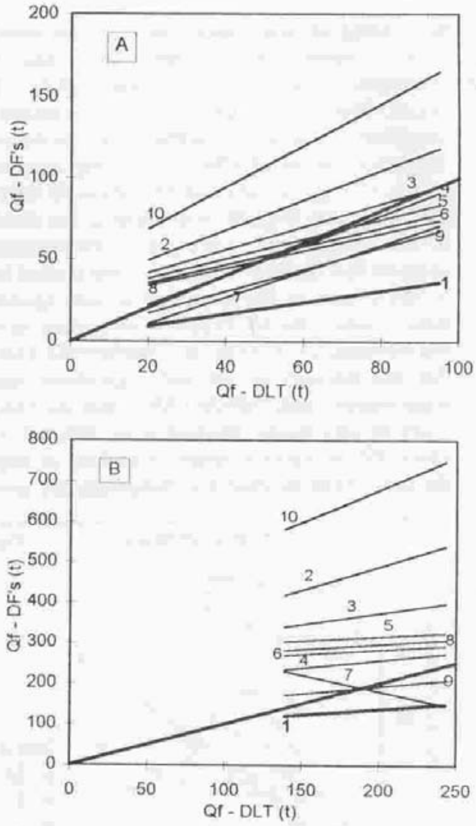
2) the search for the better regressions does not flow by a simple and systematic channel;

3) for the present there is a great lack of complementation of the present search for the support of statistics (somewhat improved) towards a better understanding of the Significant Indices of the mass of pile-driving; etc..

We trust that, if the Piling Contractors become supplied with better computational programs of easy use at the jobsite for achieving appropriate multiple regressions, and the logical sequence of 2.1 to 2.5 be followed, the volume of data forthcoming will be so great and fertile, that all the driven piling projects will be much and rapidly benefited.

We cannot fail to record the overly known fact that alongside the basic sources of the subject (Cummings, 1940; Chellis, 1951) many have been the publications (including some almost recent) of illustrious colleagues, discussing the results of DFs in practice. In the face of an extremely complex and erratic topic, we infer that in general they erred by the attitude of analysing under hopes of simple generalizable solutions, and this with insufficient data, in the light of dispersions from case to case.

We began by applying regressions directly to the most current DFs.. In Fig. 6 we present the results which lead to some conclusions of impact. 1) All the formulae behave much better in Case A, of smaller piles and loads, than in Case B, of more robust piles and loads. Perhaps the criticism might be associated with the referencing to DLTs. 2) The Coefficients of Adjustment (incorporating the Coefficients of Safety) have to be enormously differentiated from formula to formula (beware of the generalizations of Codes). 3) In most cases the relative positions (and the respective Coefficients of Adjustment) of the



Dynamic Formulae	Coefficient R^2*	
	Case A	Case B
1 - Engineering News	0,47	0,28
2 - Weissbach	0,40	0,13
3 - Stern (Universal)	0,32	0,05
4 - Wilcoxen	0,38	0,08
5 - Redtenbacker	0,26	0,01
6 - Hiley	0,27	0,02
7 - Brix & Becker	0,16	0,02
8 - Taylor	0,27	0,02
9 - Vulcan Iron	0,39	0,20
10 - Rankine	0,40	0,13

Fig. 6 - Simple regressions applied to DF's. Critique and starting impressions.

* *It is important to emphasize that for the decisions of the engineer there is little significance in the determination of R^2, it being necessary to calculate the CONFIDENCE BANDS around the regression. In this paper, one cannot enter in such details, it being sufficient to employ the R^2 as first indicators of the EXISTENCE OR NOT OF SOME CORRELATION, and, comparatively, the presumable MOST INVITING CORRELATIONS.*

different DFs resulted similar in the two cases. 4) Strangely the most rudimentary of all formulae, ENGINEERING NEWS, ended up giving (in both cases) the best R^2, and also furnished PREDICTED VALUES SOMEWHAT PESSIMISTIC, on the safe side (a correct attitude in engineering). Similarly as was mentioned with regard to the SPT (de Mello, 1971, 1985) one frequently achieves a better correlation between complex LUMPED PARAMETERS, with a large data-base, if only those parameters may be felt to be physically analogous.

Proceeding with the analyses, we present in Fig.7

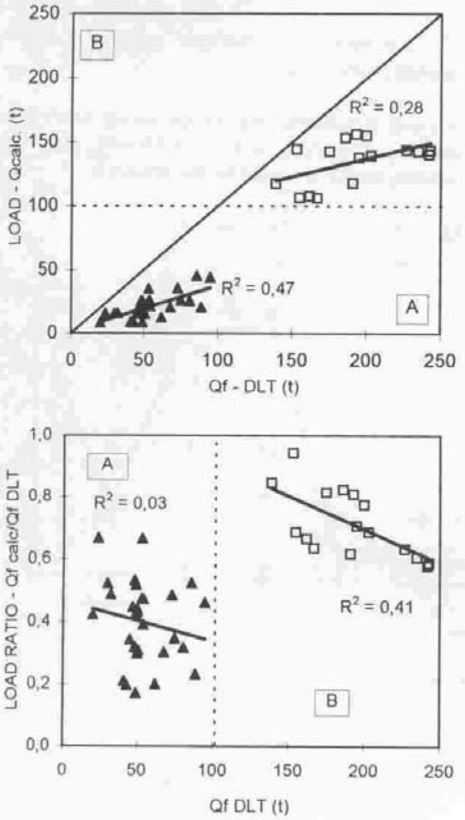


Fig. 7 - Sample minor reminders on vagaries of applied statistics. Engineering News. Same data, differently analysed.

two detailings relative to the DF Engineering News that gave the best appearances of correlation. In Fig. 7a we plotted directly the values of the nominal failure loads, as calculated by the DF vs. as "measured" in the DLTs. In comparison, in Fig. 7b we plotted the relative values, the ratios of *Qfcalc/Qf measured*. Surprisingly the conclusions invert, such that Case B of the robust piles achieves an R^2 value much better, and with a Coefficient of Adjustment calculated/measured closer to the 1.0 hoped for. As a start we must use these widely different appearances to emphasize that there are obstacles to be overcome notwithstanding the well documented hope of progressive success. The greater erraticity of Case A may be associated with relatively slender driving through preborings. The impression persists that the DLTs give nominal Q fail somewhat lower than realistic in piles of bigger diameters: if the points of Case B of Fig. 7b were all shifted somewhat to the right, there would be better similarity of the two Coefficients of Adjustment calculated/measured.

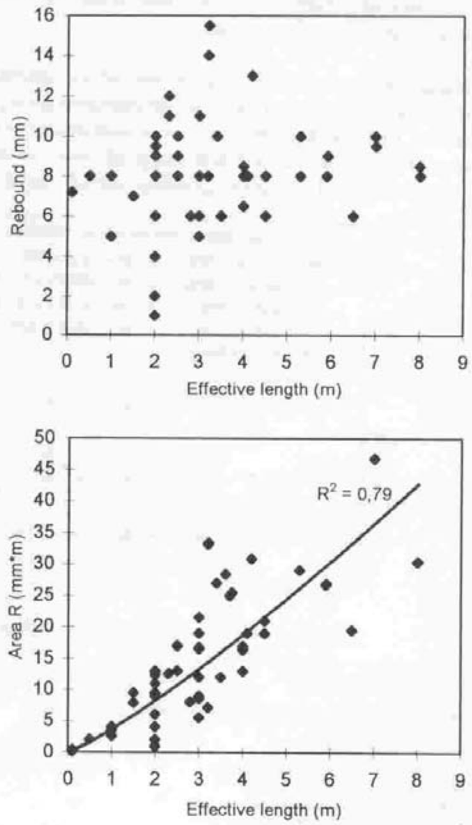


Fig. 8 - Example of spurious statistical regression.

3.5 *Example. Basic bewareness to be respected, although sometimes only revealed in the trials.*

Statistics emphasizes the need that the parameters be independent variables. On the other hand, in conceptual abstraction one reasons that everything is inter-related, nothing is strictly independent. The net result is that in the face of the complexities of the inter-relationships, the importance lies in the independence of the dominant parameters, and, sometimes this only reveals itself after obtaining the regression, and applying a critical reasoning.

Fig. 8 illustrates the type of case. The attempt to correlate rebound with embedment results chaotic, Fig. 8 a. On the other hand employing (Fig. 8b) the rudimentary parameter (rebound) x (embedment) vs. embedment, a good R^2 results for the presumed regression. Illusion, since the embedment is dominant, and it is being placed on both sides.

3.6 *Rudimentary indication of the degrees of relevance of parameters intervening in the DFs, with their observational imprecisions.*

Within each of the DFs we attempted to estimate, with relation to typical job practice (variable from job to job) with its equipments, labour and instruments, what tends to be the probable range of observational imprecision, and the corresponding consequence on the PERCENT ERROR ON THE ESTIMATED Qfail. The results, too simple to merit detailed mention, are shown in Fig. 9a. They serve to indicate which observations merit more attention, in each DF.

One of the notions generally sought for greater comfort is to "tighten on the set". We employed the "general DF" (Taylor, 1948) to confirm a practical conclusion reported in the field: under sets tighter than about 20mm/10 blows the results superpose confusedly: and this is so without taking into account the losses due to vibrations of the surrounding soil mass (which frequently increases disproportionally with tight sets). Note that at this tighter bound one reaches breakage conditions.

3.7 *An exercise of multiple regression mixing a strange index, SPT.*

A much mentioned formulation which we decided to use as an example, is that of Uto, K. et al (1985) defining the failure load by the equation:

$$Qf = A.Ec.K / (eo.L) + Nm.p..L / ef \qquad (1)$$

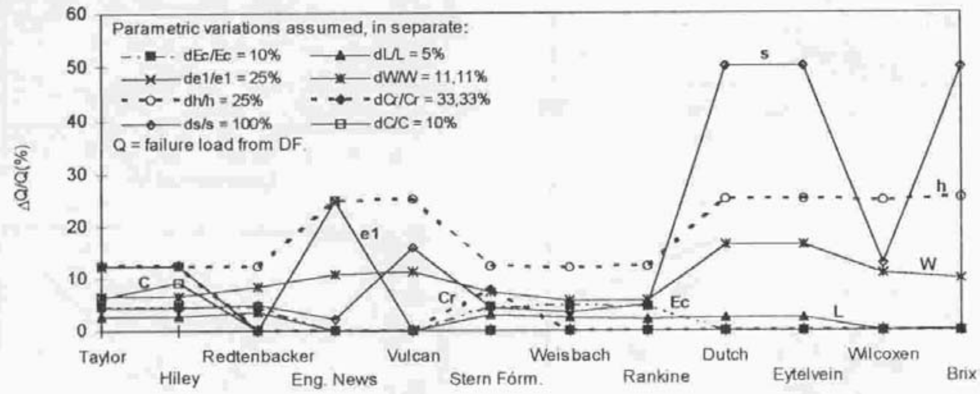
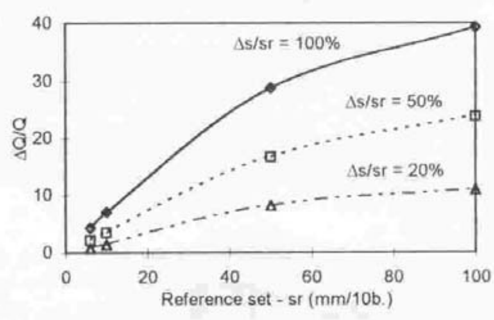


Fig. 9a - Percent influences if different observed parameters on calculated results various DF's.

s = set (mm /10b.)
Ec = modulus of concrete deformation
L = length of pile
$e1$ = fall hammer efficiency
W = weight of hammer
h = fall height of hammer
Cr = coefficient of elastic restitution
C = ratio between the actual elastic displacement of the top of the pile and bearing pile displacement



9b - Relative irrelevance in case of very tight sets.

where: N_m = mean value of SPT along the pile; $K = C2 + C3$ = elastic rebound and $C3 = s$ (set); A, p = area and perimeter of the pile. For concrete piles: $e_o = 2\ W/W_p$ (W_p = weigth of pile); $e_f = 2{,}5$.

Based on the above equation the multiple regression investigated was:

$$Qf = a.A.s + b.A + c.p.L \qquad (2)$$

The results indicated the following values: $a = 0{,}0022 \pm 0{,}0165$; $b = 0{,}139 \pm 0{,}021$ e $c = 5{,}7\text{x}10^{-7} \pm 1{,}4\text{x}10^{-7}$

The coefficient of correlation resulted $R^2 = 0{,}73$, quite favourable if compared with the other regressions analysed.

In Fig. 10a we show as a graph of areas the proportions of the total value $Q_{fail.}$ represented by each part of the above formula. It becomes evident that the part $Q1 = a.\ A.s$ may be considered negligible compared to the others. Thus, we repeated the multiple regression with only the two more significant parameters, i.e. A and pL^2. The new results furnished almost the same earlier coefficients, i.e., the formula could be written:

$$Qf = (0{,}139 \pm 0{,}021).A + (5{,}7\text{x}10^{-7} \pm 1{,}4\text{x}10^{-7}).p.L^2 \quad (3)$$

In Fig.10b we show the comparison between the measured values and those calculated using the above correlation. It is seen that the greatest part of the points lie within the band of variation of ± 20%.

3.8 *Basic orientations for ENGINEERING DECISIONS relative to the driven piling.*

We report again to the footnote regarding the frequent illusion concerning the validity of the R^2 of the regressions. They have their quick preliminary function: but the R^2 can be analogously good with absolutely different dispersions, so long as the two sides of the regression respect the equilibrium regarding moments. What matters is to arrive at CONFIDENCE BANDS around the regression: and this, including the differentiation between the confidence band on AVERAGES (possibly applicable to groups of piles) and the confidence band on INDIVIDUAL VALUES (to be respected in the case of columns supported on single piles).

One recognizes that it takes more work and is more particular, case by case, to establish such confidence bands. However, it will be a final step logically indispensable. In Fig. 11a we submit the confidence bands relative to the case A of Fig. 4.

A collateral curious revelation from Fig. 11a

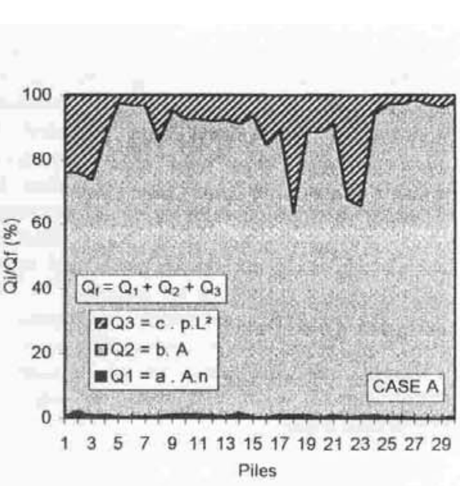


Fig. 10a - Proportional contributions of different terms

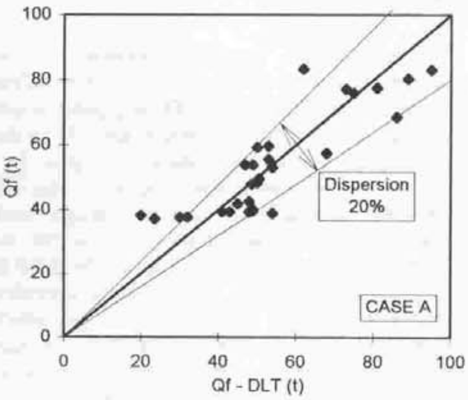


Fig. 10b - Result as simplified.

Fig. 10 - Multiple regression based on Uto's formula.

will merit specific ulterior appreciation from the simple fact, essentially inescapable, that the best regressions will rarely result being parallel to the line of equivalence calculated ≈ observed. It means that for the same pile/piling-job/D.F. the coefficient C.S. really required (to cover the negative dispersion) ends up being variable along the range of variation of the failure load (resulting from over-driving). In such a case one doubles the exaggeration in imposing any specific UNIFORM C.S. (such as 1.8).

Finally we must close with the recognition that the confirmation of having achieved the desired end-product depends on the "coverage" of the statistical universe of the piling by an adequate number of load tests, acceptably in a first stage step by the DLTs. In Fig. 11b we present an analysis of the results available from Case A showing (a) the progressively improved definition of the "average" as a function of the number of DLTs (b) starting from what number of DLTs, be it according the real chronological sequence in which they were executed, be it according to random Monte Carlo sequences, the performance of additional DLTs becomes inconsequential. It is based on such types of reasoning, and interpreted data-bases, that the requirements of the Foundation Codes should be formulated regarding numbers of load tests for piling projects.

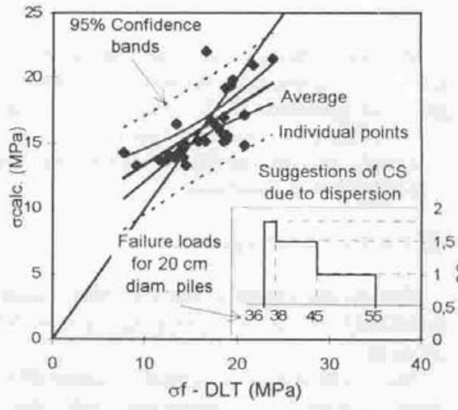
In the specific case under consideration one proves that for columns supported by groups of piles (validating statistically the use of averages) after performing 12 to 15 DLTs the remaining DLTs represented a waste.

4 PRE-ESTIMATIONS OF *Lo.k.* VIA SPT PROFILES, FOR THE SAKE OF PRELIMINARY DESIGN (item 2.1).

This is where the greatest dispersions arise, adding up the dispersions of the SPT profiles together with those of the EFFECTIVE Driving/penetration. The principal practical consequences are: (1) in the face of the Basic Design forecasting, to prepare for some margin of uncertainty with regard to the TOTAL PILING (comparison on the average, and not towards the extreme fractiles); (2) in the face of hiring the Contractor, to recognize the need to pay by driven length, per meter, (while providing the means to minimize exaggerated driving, which will cost more, even excluding breakages); (3) regarding the entire cycle of decisions 2.1 to 2.5 , to repeat the emphasis of the inescapable step which must include some Bayesian statistical treatment resorting to some DF (adjusted, improved) (itens 2.2 with 2.3).

In the years 1952-9 in Sao Paulo, with concrete piles for 25 to 50t loads and lengths of the order of 8 - 15m, in tertiary sediments effectively contributing with relative homogeneity by friction/point, the senior author accompanied with much respect (mixed with curious surprise) how the late Prof. Odair Grillo would "cast his glance" on the SPT profiles, almost one highrise building per day, and would mark in pencil the foreseen penetration length Lo.k. needed for the then required C.S = 1.5. Seeking to distill such experience he proposed (de Mello, 1977) some "preliminary rule-of-thumb suggestions" to be subjected to a critical bombardment. In principle the *Lo.k.* would depend on the cumulative ΣSPT (one result per meter), in such a manner that $\Sigma SPT \approx \sigma c$, the nominal working compressive stress on the concrete section.

In Fig. 12 we have collected a fair number of data



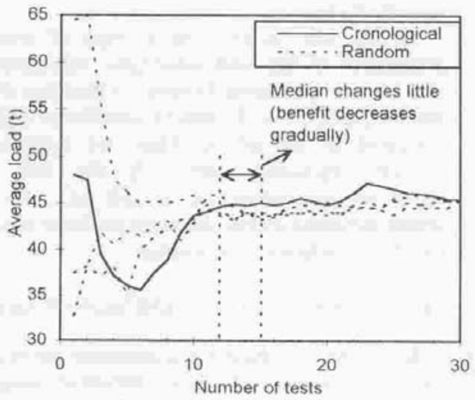


Fig. 11 - More studies of Case A regarding Codes.

points (supplied by two Companies of friends with a considerable volume of completed projects, one a Design/Consultant, Godoy and Maia, and the other a Contractor, BENATON): the data were analysed with reference to borings (1) within a radius of 5m of the driven piles (2) within a radius of 10m respectively . For each boring profile, with its profile of ΣSPT increasing with depth, the points are plotted for the ΣSPT corresponding to the driven *Ls*, minimum and maximum.

None of the columns/buildings had any problem. Thus, we should only be interested in the Lmin.. We have already seen that it is not difficult to drive more than the length effectively necessary, and overdriving tends to be an understandably sought-after practice. In these sets of data there were very few cases in which the unconfessable rule-of-thumb resulted absurd. Within our earnest concern for respecting the priority for theorizations, and fully conscious of the crudity of such "rule-of-thumb suggestions" that

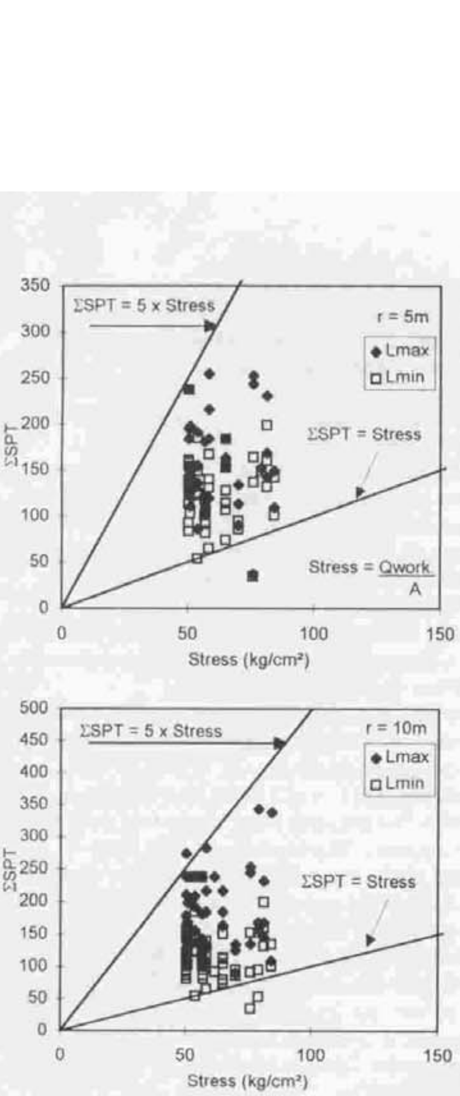


Fig. 12 - Testing one "rule-of-thumb" offer (1977).

are INEXORABLE WITHIN THE INTENSITY OF PROFESSIONAL PRACTICE, we repeat what was emphasized in the specific International Congress, 1977, that the suggestion was (and now is again) merely offered for sacrificial imolation, to enjoin the Piling Contractors, immeasurably documented, not to fail to expose their practices of inner intimacy.

For closing the present paper we report to Fig.13 wherein we return to Cases A and B. In Fig 13a we indicate the dispersions pertaining to the borings: although integrations attenuate the point-dispersions (erratic SPTs), one notices that in the final use, FOR DECISION, the dispersions of $\sum$SPT are still very great. However, reasonable trends are not overthrown, but only confirmed: in the sediments, B, the dispersions are much smaller than in the dense granite-gneiss saprolites, A. Would there be any chance of decreasing the SPT erraticities, densifying more the borings, to decrease the erraticities on the consequences? In part, yes: however, never to the point of dispensing the quality control PILE AFTER

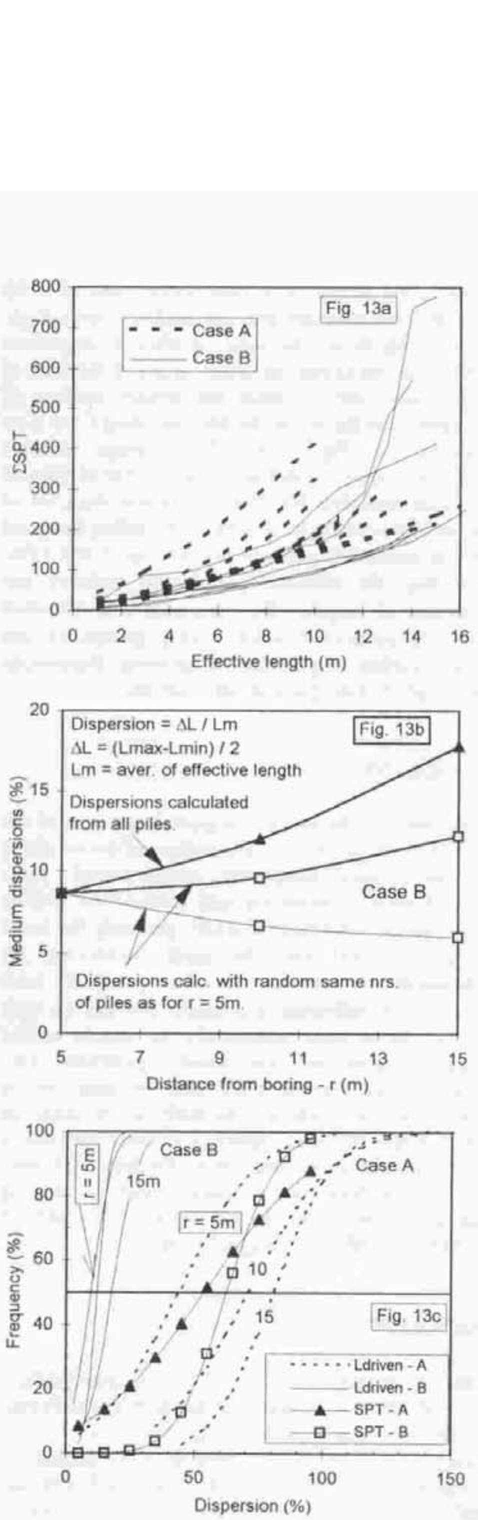


Fig. 13 - Dispersions of borings and effect. lengths L.

PILE, each pile defining by its very driving the actual penetration profile, principally in cases type A.

Figs. 13b,c offer some interesting collateral analysis. Fig. 13c gives the cumulative frequency curves of dispersion (%) of L, associated with each boring, using all the Ls of piles within radii of 5, 10 and 15m. One confirms also the medians increasingly more distant (from the ideal of 0%) of dispersion with increasing radius. In order to avoid the bias of interpretation derived from the greater number of data (piles) we furthered the analysis using Case B to compare, in Fig. 13b, the average percent dispersions, always using the same number of piles as had been available for the 5m radius limit. It is interesting to conclude (in favour of bidding budgets) that the average dispersions lay between 5 and 17%. Also, that the effective pile-driving widened the dispersion of lengths: the maximum and minimum limits for random (Monte Carlo) groups of the smaller number of piles led to narrower dispersions than resulted in the piles as really driven.

5 CONCLUSION.

We submit that the successive participations of all the steps of the logic of design/execution of driven piling jobs have been adequately demonstrated. In a separate paper a more rational formulation will be submitted for the link of the DF, presently the most harshly criticized and the most withdrawn for understandable reasons. In the practical level however the following procedure prevails as very realistic: to validate statistically by simple and/or multiple regressions the most applicable DF, recognized as variable from case to case, to be adjusted at each job-site as early as possible as driving starts. What is important is that Contractors document themselves and the profession, with their valuable professional practice, without feeling ashamed of using the ever present COEFFICIENTS OF ADJUSTMENT ("bugger factor").

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